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Conceptual study of scroll-type rotary gasoline Internal Combustion Engine

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Abstract

This paper reports the study of a conceptual gasoline Internal Combustion Engine (ICE) using scroll type rotary device rather than conventional piston as the main engine component. The proposed innovate engine adopts Humphrey Cycle to maximize the power performance of ICE. A performance comparison of the Humphrey Cycle, Otto cycle and Brayton cycle has firstly been conducted and studied. The effects of using different designed compression ratio under variable expansion ratio have been investigated, which identify the optimal operational conditions under different compression/expansion ratio of the engine. A case study has been conducted to study the performance of small scale scroll-type rotary ICE. Results pointed out under designed compression ratio from 2:1 to 10:1 the effective energy efficiency of the scroll-type rotary ICE ranges from 0.41 to 0.55 and the effective power from the system ranges from 2.88 to 15.82 kW.

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Keywords: Scroll-type rotary device, Humphrey Cycle, Internal Combustion Engine, Performance study

1. Introduction

Increasingly attentions are focusing on the environmental problems caused by burning fossil fuels. The development of more efficient, more compact and cost effective Internal Combustion Engine (ICE) can potentially improve the overall energy efficiency through burning fossil fuels, reduce the emissions compared with conventional engine and generate more effective engine shaft power. Gasoline engines and diesel engines are two

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most well know ICE technologies [1]. The higher of the compression ratio, the higher overall efficiency of the ICE can be obtained. However, typical compression ratio of gasoline engines ranging from 7:1 to 10:1, which is much lower than that of typical diesel engines. The development of high efficient gasoline engine to operate in low compression ratio can potentially solve this problem. Moreover, the piston-type gasoline and diesel engines both waste high pressure energy at the end of expansion process [1, 2]. The gas turbine engines using the same combustion process as diesel engines can perform full expansion process, which can produce much higher power than diesel engines under the same operational conditions [1, 3]. On the other hand, the scroll type rotary device has the advantages of compact, low noise, high efficiency and low cost, which has been widely used in small scale power generation system such as Organic Rankine cycle [4-8]. In this paper, a Scroll-type rotary Internal Combustion Engine using Humphrey Cycle has been proposed and studied, who adopts full expansion process similar as gas turbine engines and can be potentially used to burn gasoline with much lower compression ratio compared with typical gasoline engine.

2. Description of the Scroll-type rotary Internal Combustion Engine

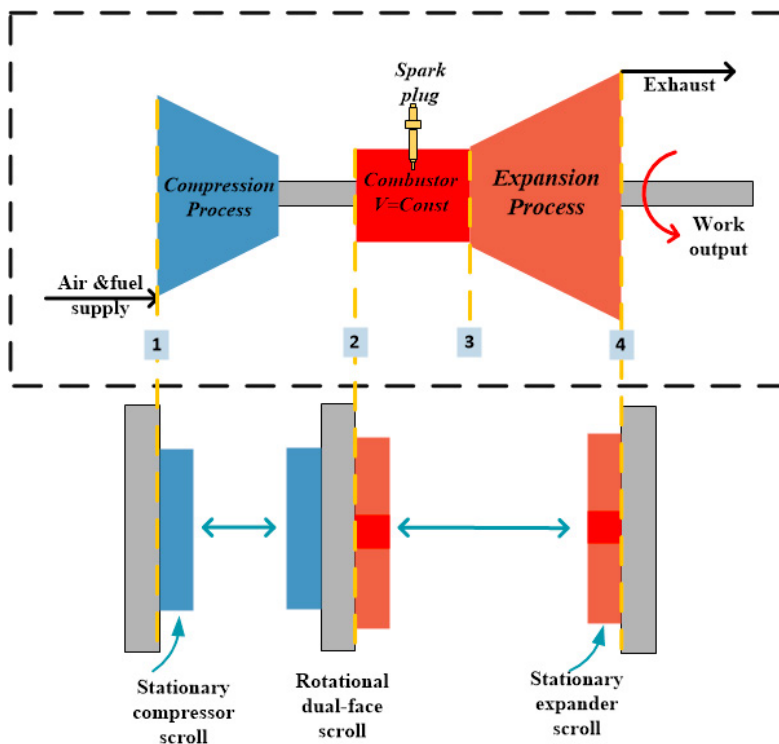
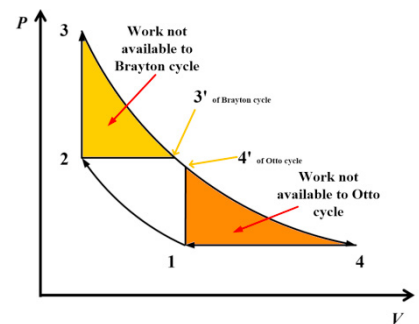
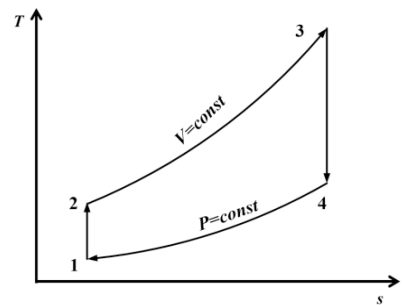


Fig. 1. Schematic diagram of scroll-type rotary ICE



(a)



(b)

Fig. 2. (a) P - V diagram, (b) T - s diagram

Fig. 1 shows the schematic diagram of the scroll-type rotary ICE. The working process can be described as follows. From point 1 to 2, the air and fuel mixture is supplied to the compressor part of the engine. The rotational dual-face scroll starts to rotate and compress the mixture from the suction area to the centre of the two scrolls in order to form the high pressure mixture as illustrated in Fig.3 compressor mode. The compressed air and fuel mixture flows through the center port of the rotational dual-face scroll from the compressor side to the expander side. The combustion process happens in the chamber of the expander side of the engine as illustrated in Fig. 1. The mixture of high pressure air and fuel is ignited by the spark plug, when the two chambers A1 and A2 finish the suction

process as shown in Fig. 3 under the crank angle $\theta = 0$. Due to the combustion process is ignited in two fixed chamber, this process can be recognized as the constant volume combustion. The working process from Point 2 to 3 can therefore be drawn as Fig. 2. After the combustion process, the expansion process immediately starts, which is illustrated as the expander mode in Fig. 3. The high temperature/high pressure gases drive the expander part of the scroll-type rotary ICE. The work produced from the ICE is obtained from the shaft connected on the rotational dual-face scroll. The exhaust gases from the ICE are released directed to the environment at the exhaust port of the expander side of the engine, which means full expansion process can be obtained.

3. Evaluation methods

In this study the idea thermal energy efficiency of Humphrey cycle, Otto cycle and Brayton cycle has firstly been studied and compared. The calculated conducted in this part sets the combustion temperature at 1600 °C (T_3 in Fig. 2) and the environmental temperature at 30 °C. The working fluid has been recognized as idea gas. The effects of exhaust gases and chemical reaction processes burning fossil fuel are ignored.

The second part of this work has been conducted to evaluate the effects of geometric relationship on the scroll-type rotary ICE overall performance. In the compression process, the work consumed by the compressor part of the engine is defined as Eq. (1) [11], where Point 2_d is the designed working point defined by the geometric parameter of the scrolls under isentropic expansion process.

$$\dot{W}_{com} = \dot{m} \cdot [(h_{2_d} - h_1) + (P_2 - P_{2_d}) \cdot v_{2_d}] \quad (1)$$

The energy provided to the engine during combustion process is calculated by the following equation, where assumes 80% of overall fuel energy can be obtained by the engine. ($\eta_{2-3} = 0.8$)

$$\dot{Q}_{combustion} = \dot{m} \cdot (h_3 - h_2) \cdot \eta_{2-3} \quad (2)$$

The work produced from the expander side of the engine can be calculated by Eq. (3), where h_{4_d} is the designed exhaust specific enthalpy of after the isentropic expansion process.

$$\dot{W}_{exp} = \dot{m} \cdot [(h_3 - h_{4_d}) + (P_{4_d} - P_1) \cdot v_{4_d}] \quad (3)$$

The overall thermal efficiency of the scroll-type rotary ICE can be defined as

$$\eta_{scroll_ICE} = (\dot{W}_{exp} - \dot{W}_{com}) / \dot{Q}_{combustion} \quad (4)$$

The mass flow rate of the fluid is calculated by the Eq. (5), where $V_{combustion}$ is the combustion volume of the scroll rotary ICE per turn.

$$\dot{m} = \frac{N}{60} \cdot \frac{V_{combustion}}{v_3} \quad (5)$$

4. Results and discussion

4.1 Performance comparison of Humphrey cycle, Otto cycle and Brayton cycle

The scroll-type rotary Internal Combustion Engine adopts Humphrey cycle throughout the operations as previously described. The ideal thermal efficiency of the Humphrey cycle, Otto cycle (gasoline engine) and Brayton cycle (gas turbine engine) under different compression and pressure ratio has been studied and compared. In order to

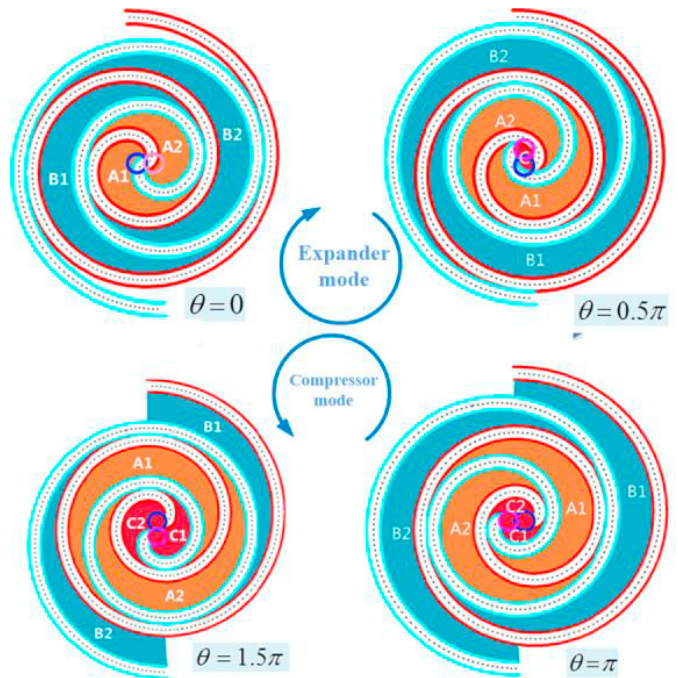


Fig.3. Schematic diagram to illustrate the working principle of scroll device [9, 10]

avoid misfire, the compression ratio of a typical gasoline engine ranges from 7:1 to 10:1, which limits the overall thermal efficiency within the highlighted area as shown in Fig. 4. The maximum ideal thermal efficiency of a gasoline engine under 10:1 compression ratio is about 0.55, which can be achieved by gas turbine engine using Brayton cycle under around 8:1 compression ratio. On the other hand, the novel scroll-type rotary Internal Combustion Engine using Humphrey cycle only requires the compression ratio as low as 2.05 to achieve the same overall thermal efficiency of the Otto cycle under the maximum compression ratio.

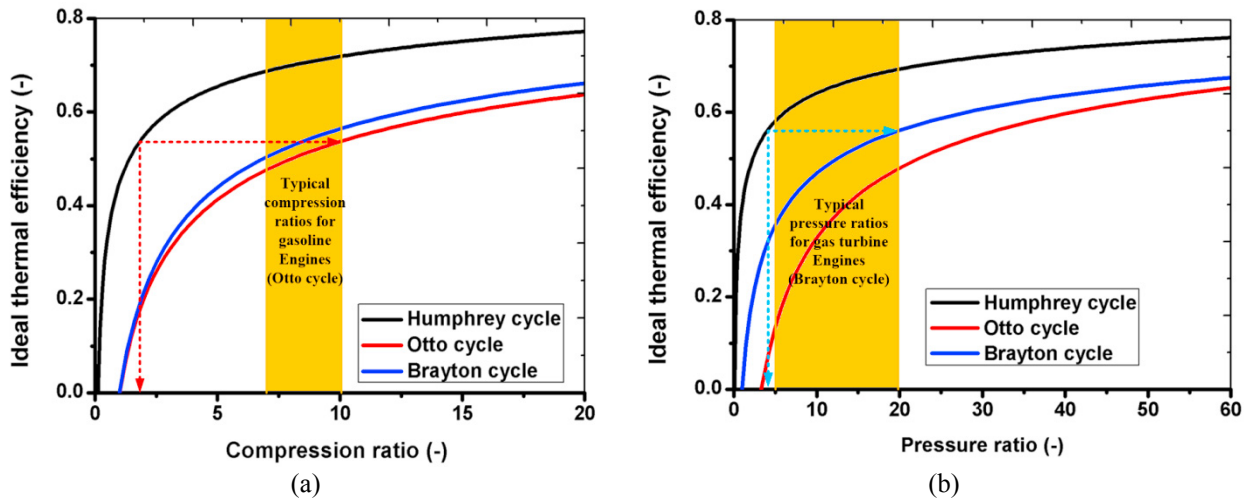


Fig. 4. Comparison of ideal thermal efficiency of Humphrey cycle, Otto cycle and Brayton cycle (a) under different compression ratio, (b) under different pressure ratio

Typical gas turbine engines can be operated under the pressure ratio from 5 to 20 as the highlighted area in Fig. 4 (b), which illustrates the theoretical overall thermal efficiency of gas turbine engine can always be higher than that of gasoline engine under the same pressure ratio. Results pointed out the maximum thermal efficiency of Brayton cycle within the operational conditions of typical gas turbine under pressure ratio at 20:1 is about 0.56, which can be achieved by the Humphrey cycle under the pressure ratio at 4.1. The results clearly presented under the same designed operational conditions the performance of Humphrey cycle is far better than that of Otto cycle and Brayton cycle. Moreover, the scroll-type rotary Internal Combustion Engine adopting Humphrey cycle can achieve the same overall thermal efficiency as that of typical gasoline engine and gas turbine engine under relatively low compression and pressure ratio, which means the cost of material used in the scroll-type rotary Internal Combustion Engine can be much lower than that of typical gasoline engine and gas turbine engine.

4.2 Effects of designed compressor compression ratio on the scroll-type rotary Internal Combustion Engine

Other than piston type ICE, the scroll-type ICE can be operated using different volume compression/expansion ratio during the compression and expansion processes. The effects of variable compression/expansion ratio of the compressor/expander side of the scroll-type rotary ICE have been studied. Five compression ratios of the compressor side are selected to represent the influence of changing expansion ratio on the performance of the engine. Results indicate the optimal overall energy efficiency of the scroll-type rotary engine exist within the engine compression ratio from 2:1 to 10:1. At the optimal performance point, the designed expansion ratio of expander side is much higher than the compression ratio of compressor side. Fig. 5 (a) shows the optimal performance can be achieved under the compression/expansion ratio at 2:1/5.1:1, 4:1/9.5:1, 6:1/13:1, 8:1/14:1 and 10:1/16.5:1, when the energy efficiency of the system can be respectively achieved at 40.92%, 48.02%, 51.52%, 53.62% and 55.24%. The wasted energy ratio of the overall supply energy has also been evaluated under different compressor/expander ratios

and the results are plotted in Fig. 5. Results show the minimum dumped energy ratio under the compression ratio at 2:1, 4:1, 6:1, 8:1 and 10:1 are around 39%, 32%, 28%, 26% and 24%, respectively.

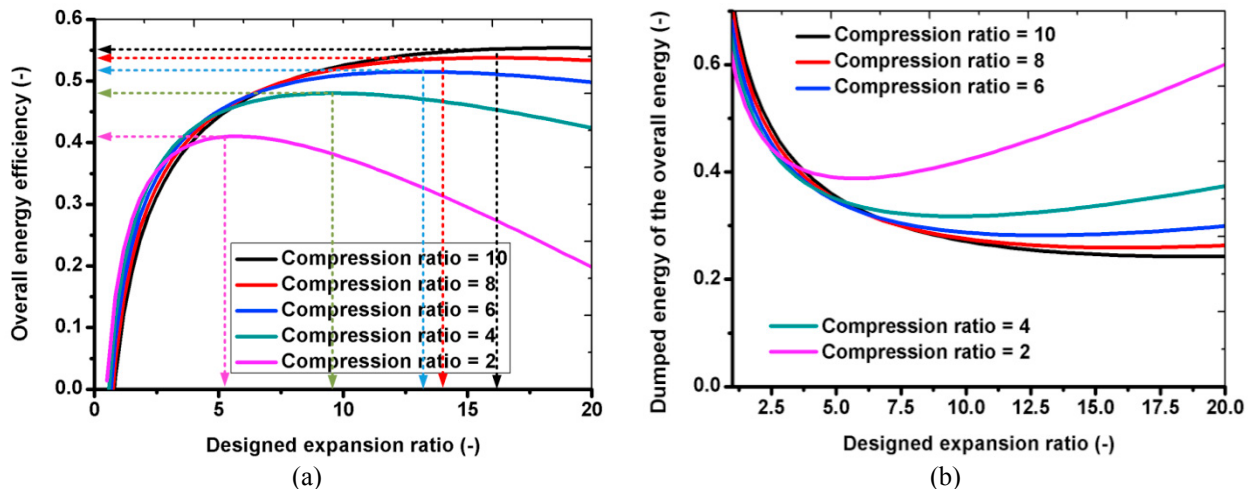


Fig. 5. Effects of designed compressor compression ratio on the (a) energy efficiency of the scroll-type rotary Internal Combustion Engine, (b) dumped energy of the overall energy

4.3 Performance evaluation of small scale scroll-type rotary Internal Combustion Engine

A case study has been conducted in order to predict the performance of the scroll-type ICE. Due to the fact that scroll device are more suitable to be used for small scale application, the case study conducted in this part has set the combustion volume of the scroll engine at 35 cm^3 . And the rotational speed of the engine has been selected and fixed at 3000 rpm in the calculation, because the selected speed is favourable to be used for scroll device and the engine can be directed connected to conventional electricity generator under the designed rotational speed. The compression/expansion ratio of the small scroll engine has been set at the optimal designed parameters as obtained in previous section. The effective energy of the small scale scroll-type rotary engine under the designed geometric parameters for combustion, compressor driven, dumping wasted energy and generating effective power are plotted in Fig. 6. The effective power generated from the engine under the designed compression ratio at 2:1, 4:1, 6:1, 8:1

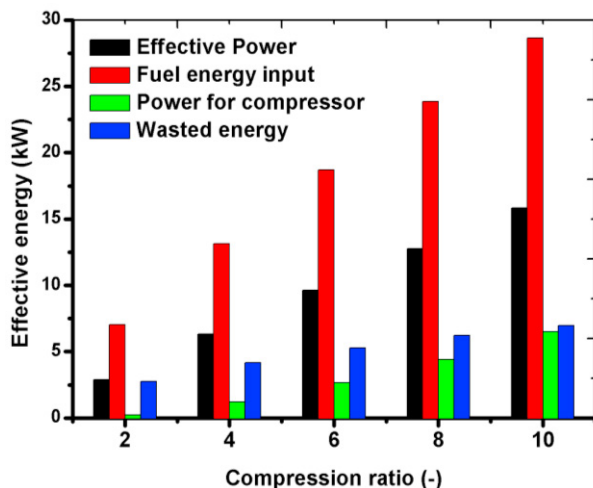


Fig. 6. Relationship between effective energy and designed compression ratios

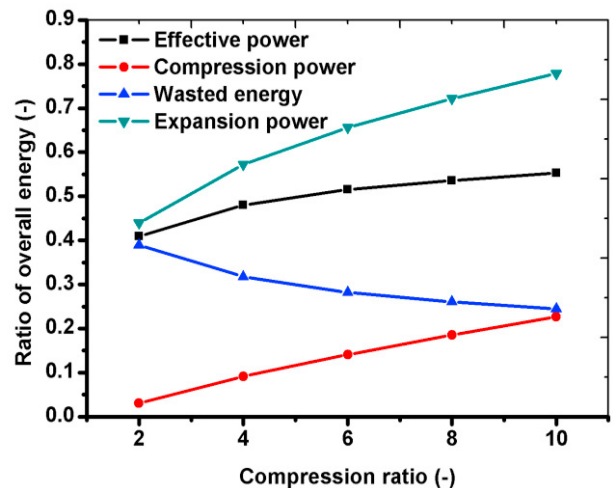


Fig. 7. Ratio of overall energy under different designed compression ratio

and 10:1 is respectively 2.88, 6.31, 9.63, 12.78 and 15.82 kW illustrated in Fig. 6. Moreover, the ratio of the mentioned four parameters of the novel ICE under different designed compressor ratio has also been plotted in order to study the tendency relationship as shown in Fig. 7.

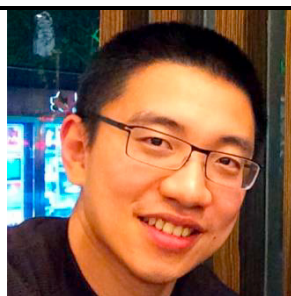
Results indicated with the increase of designed compression ratio the work occupying the overall input energy required to drive the compressor side of the engine is increased from 3.08% to 22.65% under designed compressor ratio from 2:1 to 10:1. The lines of effective power, compression power and expansion power shown in Fig. 7 indicate the overall effective energy efficiency of the scroll-type rotary ICE ranges from 0.41 to 0.55 under designed compression ratio from 2:1 to 10:1. The wasted energy from the engine is higher than that to drive the compression process and more wasted energy can be observed under relatively lower designed compression ratio, which means a wasted energy recovery system will be desirable under low compressor ratio of the engine.

5. Conclusions

In this study, a scroll-type rotary gasoline Internal Combustion Engine using advanced power generation cycle (Humphrey Cycle) has been proposed and studied. The ideal thermal efficiency of the Humphrey cycle, Otto cycle (gasoline engine) and Brayton cycle (gas turbine engine) under different compression and pressure ratio has been studied and compared. Results indicate under the same designed operational conditions the performance of Humphrey cycle is far better than that of Otto cycle and Brayton cycle. The effects of variable compression/expansion ratio of the compressor/expander side of the scroll-type rotary ICE have then been studied. And results show the optimal performance can be achieved under the compression/expansion ratio at 2:1/5.1:1, 4:1/9.5:1, 6:1/13:1, 8:1/14:1 and 10:1/16.5:1, when the energy efficiency of the system can be respectively achieved at 40.92%, 48.02%, 51.52%, 53.62% and 55.24%. A case study has been conducted to predict the performance of the novel scroll-type rotary ICE with fixed combustion volume, which indicate under designed compression ratio from 2:1 to 10:1, the effective power from the system ranges from 2.88 to 15.82 kW.

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Biography

Dr Yiji Lu, born in June 1989, is currently a research associate in Newcastle University. He graduated from Shanghai Jiao Tong University in 2011 for his bachelor degree, he conducted his M.Phil. and Ph.D. in Newcastle University in 2012 and 2016. His research interests include but not limited to advanced waste heat recovery technologies, engine thermal management, advanced engine development, engine emission technologies, chemisorption cycles and expansion machines for power generation system. He has been regularly invited to review the manuscripts for the scientific journals including Applied Energy, Applied Thermal Engineering, Energy (the International Journal), and Energy for Sustainable Development.

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